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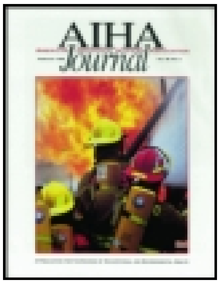

American Industrial Hygiene Association Journal

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/aiha20

Performance characteristics of the 10 mm cyclone respirable mass sampler: part I — monodisperse studies

KNOWLTON J. CAPLAN [a], LAURENCE J. DOEMENY [b] & STANLEY D. SORENSON [c]

[a] University of Minnesota, Minneapolis, MM

[b] NIOSH, Cincinnati, OH

[c] 3M Company, St. Paul, MN

Published online: 04 Jun 2010.

To cite this article: KNOWLTON J. CAPLAN, LAURENCE J. DOEMENY & STANLEY D. SORENSON (1977) Performance characteristics of the 10 mm cyclone respirable mass sampler: part I — monodisperse studies, American Industrial Hygiene Association Journal, 38:2, 83-95

To link to this article: http://dx.doi.org/10.1080/0002889778507918

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The 10 mm cyclone respirable mass sampler was evaluated to determine the flow rate which best matched the BMRC and the LASL-ACGIH criteria and to determine effects of pulsating flow, particle charge, mass loading and sampler orientation. Part I, this paper, describes the work with monodisperse aerosol The best match for BMRC was 1.4 lpm; for LASL, 1.7 lpm. The two separate criteria should be merged. The 10 mm cyclone is better for sampling logistics than the BMRC horizontal elutriator.

Performance characteristics of the 10 mm cyclone respirable mass sampler: part I — monodisperse studies

KNOWLTON J. CAPLAN,* LAURENCE J. DOEMENY** and STANLEY D. SORENSON***

*University of Minnesota, Minneapolis, MN; **NIOSH, Cincinnati, OH; ***3M Company, St. Paul, MN

Introduction

The objective of this research was to evaluate the performance of the coal mine dust personal sampler, also called the "respirable mass sampler." The quantitative effect of pump pulsating flow, particle charge, mass loading, and sampler orientation was determined.

For the purposes of this study, the investigation singularly involved the characteristics of the 10 mm cyclone portion of the sampler. It was assumed, for example, that the filter captured essentially 100 percent of the particles penetrating the cyclone under all conditions of operation. Mechanical parameters such as battery life, accuracy of pump flow meters as delivered, etc. were not included in the study but instead were kept constant or compensated by laboratory procedures.

The evaluation of the cyclone included obtaining penetration curves using monodisperse aerosols of several diameters for three sampling flow rates and three levels of pulsation at each rate. Polydisperse coal dust was used to evaluate the effects of particle charge, sampler orientation, air velocity, and mass loading. Results were compared to the respirable coal dust criterion of British Medical Research Council (BMRC)[1-3]; to the respirable mass dust criterion of the Los Alamos Atomic Energy Commission (LASL); and to the American Conference of Governmental Industrial Hygienists (ACGIH) similar criterion.

The project was divided into two parts, the first part dealing with monodisperse aerosol and the second with coal dust. For the monodisperse work cyclone penetration curves were obtained by measurement of the falling speed in a modified Millikan falling particle apparatus. Although this method is inadequate for polydispersè aerosols due to the small number of particles measured, it is satisfactory for monodisperse aerosols. Size distribution was determined by optical microscope. Sphericity of particles was checked by electron micrography.

The cyclone penetration was determined by using ^{113}In tracer in the colloidal solution from which the aerosol was produced. The amounts retained in the cyclone and the amounts penetrating the cyclone (collected on the filter) were quantified. Use of the tracer technique permitted short sampling times and multiple replication.

This work was performed in connection with National Institute for Occupational Safety and Health Contract No. PH-CPE-R-0036.

For more information about authors, see "this issue's authors . . ." on page A-3

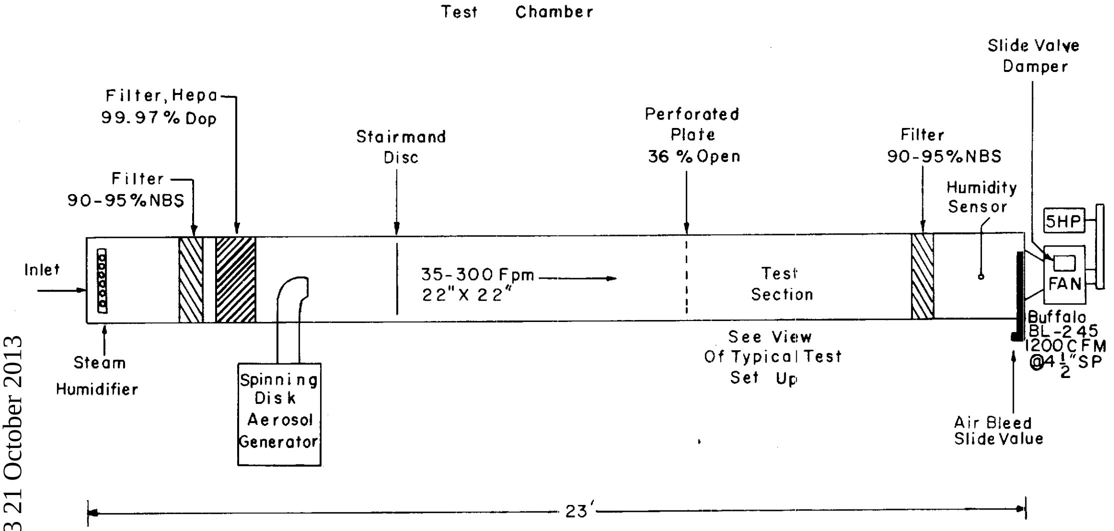


Figure 1 – Schematic view of dynamic test chamber.

The experimental equipment and procedures were calibrated and the experimental error evaluated in all areas which would have a significant effect on the results obtained.

experimental

dynamic test chamber

The test chamber used is shown schematically in Figure 1. Aerosol was introduced into the filtered air stream from a spinning disc generator (later, from a coal dust feeder). A Stairmand disc insured thorough mixing of the aerosol, and a perforated plate upstream of the test section provided a uniform flow profile. The chamber air velocity was controlled by adjustment of the blower speed and/or air-bleed slide valve. The uniformity of air flow velocity and aerosol concentration in the test area was evaluated. Air velocities were measured with an Alnor 8500 Thermoanemometer.^{TM} A sixteen-point traverse of the test section area was made with the anemometer probe held in a test stand. Individual readings were within ± 10 percent of the mean velocity of .254 mps (50 fpm). A 35.56 x 30.48 cm (14 x 12 in.) area in the center of the test section was measured to represent the location of sampling equipment. A fifteen-point traverse of this area indicated individual velocity readings within ± 2 percent of mean velocities of 1.524 mps (300 fpm).

Uniformity of aerosol concentration was evaluated by generating iron oxide aerosol tagged with ^{113}In with the spinning disc generator. Samples were taken with four membrane filters placed horizontally across the sampling area. After sampling for 30 minutes at 2 liters per minute, the activity on the filters was counted with a gamma spectrometer as representing the aerosol collected. The concentration measured on all filters within ± 5 percent of the mean. The particle size was approximately 4μm. Velocity in the chamber was .254 mps (50 fpm).

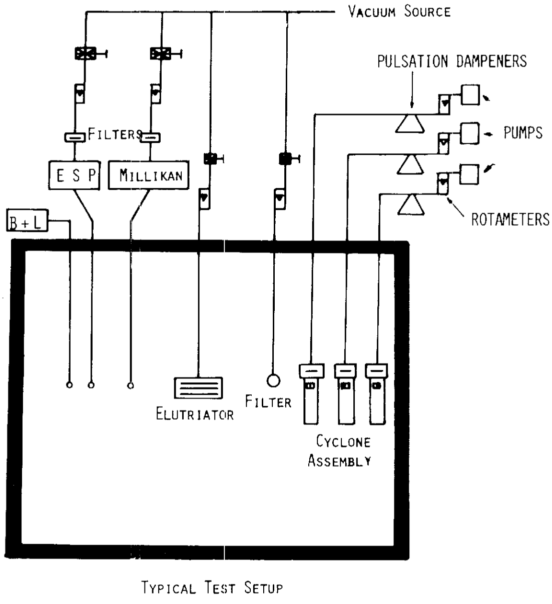


Figure 2 – Arrangement at test section.

Figure 2 shows the arrangement of sampling equipment at the test section during a typical run. From left to right, the function of the sample station components was as follows:

(1) *B & L*: Bausch and Lomb Model 40-1A light scattering photometer with digital readout, used as a control device to insure uniformity of conditions during the run. For coal dust tests, uniformity of particle size distribution was also monitored.

(2) *ESP*: A point-to-plane electrostatic precipitator for collecting particles on electron micrograph grids. Micrographs were inspected for visual sphericity of particles.

(3) *Millikan*: The modified Millikan falling drop apparatus, used to measure the terminal velocity of particles during the monodisperse portion of the project.

(4) *Elutriator*: An elutriator furnished by the National Institute of Occupational Safety and Health, a duplicate of the British Mines Research Establishment (BMRE) elutriator head, used for collection of aerosol according to BMRC criteria.

(5) *Filter*: An open-face plastic, 37 mm diameter filter holder, using 5 μm pore size Gelman Vinyl Metrice^{TM} filters.

(6) *Cyclone assembly*: Three 10 mm nylon cyclone and filter assemblies, operated at different degrees of pulsation at the sample flow rate.

The array of sampling equipment varied with different phases of the investigation. The above description applies to the bulk of the monodisperse work.

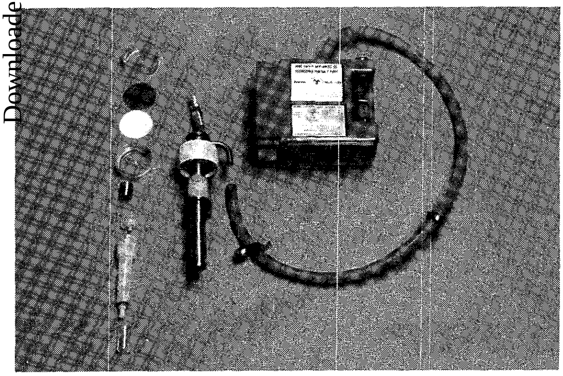


Figure 3–Respirable mass sampler.

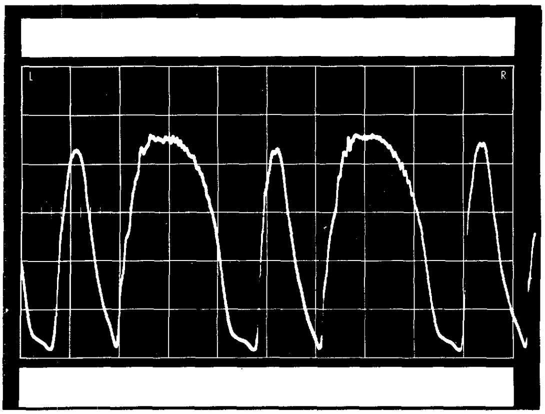


Figure 4–Pump pulsation. Average air flow 2.0 lpm; scale 1.1 lpm per division, 5 milliseconds per division.

personal samplers

Mine Safety Appliance Company personal pumps, Model G, were used with MSA 10 mm nylon cyclones and filter holder assemblies. The apparatus is shown in Figure 3.

An attempt was made to include Unico Micronaire^{TM} pumps, but difficulty was experienced with delivery and operation of the equipment. For this reason, use of the Unico equipment was dropped in order to avoid delay of the project. The Unico sampler is functionally identical to the MSA, the only important difference in regard to this study being the frequency and magnitude of the pulsations of flow.

MSA pump pulsation, when operating on a sampler, had a frequency of 38 Hz and a magnitude of 2.5. Pulsation is defined as

$$\text{Pulsation} = \frac{(\text{max flow}) - (\text{min flow})}{\text{average flow}}$$

An oscilloscope trace of the MSA is shown in Figure 4. The trace was obtained from the output of a fast response (1000 Hz) temperature compensated anemometer (Thermo Systems Model 1051-1, 1054B-36A, 1352B)^{TM} in the air line downstream of the sampler.

filters

The filters used were Gelman No. 60714, 37 mm diameter, 5 micrometer pore size Vinyl-Metricel^{TM} VM-1 membrane filters. For the monodisperse work, particulate material on the filter was measured by gamma-ray spectrometer. In the coal dust experiments, coal dust on the filter was determined by tare and gross weighings on a Cahn Model RG^{TM} electrobalance operated in a "laminar flow" clean room controlled at constant temperature and humidity. The filters were allowed to come to equilibrium for a minimum of one hour with the room atmosphere before weighing.

aerosol production --monodisperse

Ferric oxide microspheres were produced using an Environmental Research Corporation Model 8330^{TM} spinning disc aerosol generator. An alcoholic solution of colloidal dialized β ferric oxide was continuously fed onto a 2.54 cm (1 in.) diameter disc, spinning at 60,000 rpm, with a continuous drive syringe pump. The liquid spins off the disc and breaks up into liquid droplets which subsequently evaporate, leaving nearly spherical aggregates of iron oxide. The size of the final particle depended upon the initial concentration of ferric oxide used.

The colloidal iron solution was made by diluting from 0.5 to 2.0 ml of β-Fe_20_3 Aquasol^{TM} (obtained from Diamond Shamrock Corporation) to 25 ml with 90 percent ethyl alcohol. The diluted solution was made up fresh for each experiment because it proved to be unstable after standing several hours. The ^{113}In tracer was obtained from a sealed, self-contained ^{113}In generator (New England Nuclear Model NRP-016)^{TM} as the decay product of ^{113}Sn. The indium was eluted by drawing 0.05N HCl over the metal surface and into a small vacuum vial. The elution volume was approximately 5 ml, containing enough activity for two experiments lasting approximately four hours. Two ml of the ^{113}In solution was mixed with 25 ml of the dilute sol. prior to use in the aerosol generator.

optical sizing

The aerodynamic diameter was determined by the modified Millikan apparatus as described, but the number of particles so measured was too small to provide a measure of the dispersion of particle size. Optical sizing was used for dispersion estimates. Samples were taken for the duration of each run at 2 lpm on a .5μm pore size membrane filter mounted in an open-face plastic holder. The filter was mounted dry for sizing by microscope at 430x magnification using a Porton reticle. At least 100 particles were measured on each slide. Sizes were classified in groups of sizes estimated to the nearest 1/2 Porton circle size. The data was plotted on log probability paper and σ_g determined as the ratio of the (cumulative) 84.1% size to the 50% size. Resulting values of σ_g ranged from 1.04 to 1.13 and averaged 1.08.

For the penetration curves (Figures 5, 6, 7) the observed aerodynamic diameter was plotted as the abscissa, σ_g assumed equal to 1.00. It is possible to convert the count distribution to mass distribution by the Hatch-Choate equation[4] and then to apply the computations made by Lynch[12] to estimate the error in penetration curve data caused by the assumption of $\sigma_g = 1.00$. On this basis, the error that would be caused by use of aerosol with $\sigma_g = 1.1$ was estimated a follows:

Count Median Diameter	% Error in Penetration Relative to $\sigma_g = 1.00$
2	-5.7
3	0.0
4	0.24
5	-0.8
6	-9.0

Thus the error in penetration curve data from this cause is negligible for all but the 6 μm size, and at that size is less than the variability of the raw data. This estimate also concurs with that of Moss and Ettinger[13] who selected an aerodynamic diameter of 3.8 μm as a size at which the cyclone was insensitive to σ_g.

aerodynamic sizing

Aerodynamic particle diameter was measured using a photographic version of a Millikan falling particle apparatus. In this apparatus, a particle is admitted by gravity into a small hole in the top of a quiet zone. A chopped laser beam is directed horizontally across the quiet zone, with a low power microscope eyepiece and film holder mounted so as to collect forward-scattered light from a particle falling through the laser beam. The apparatus has been described in detail.[5] The light source used here was a 3.5 milliwatt He-Ne multimode continuous wave laser, chopped at 10 Hz or 4 Hz; the light duration was about 10-percent-on/90-percent-off for each cycle. Equally-spaced dots on the film resulted from a particle falling at constant speed. The image on the film was projected onto a screen and the distance between the dots

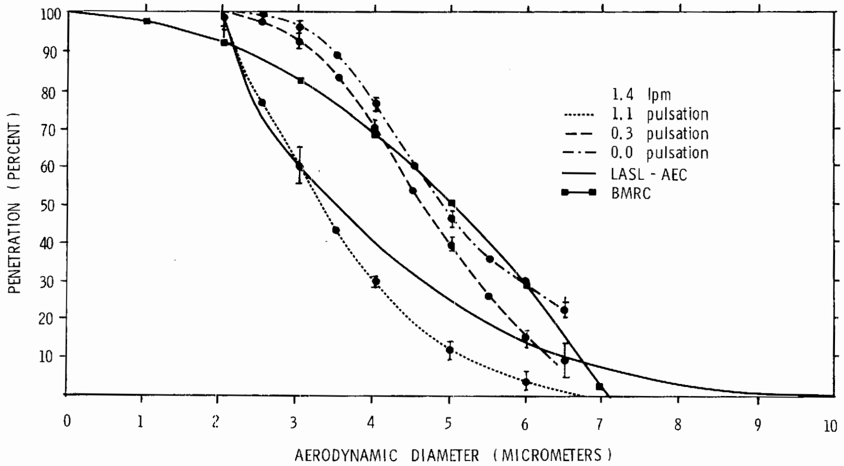


Figure 5 – Plot of polynomial curve fit of experimental data at 1.4 lpm. Error bars are the 95 percent confidence limits.

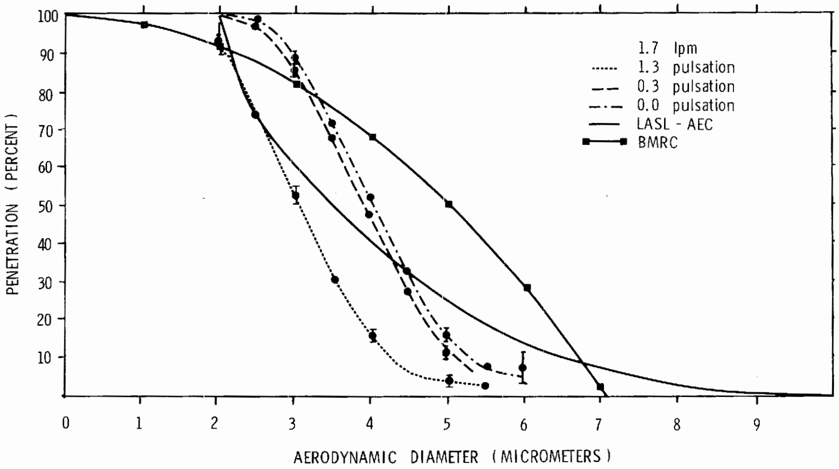


Figure 6 – Plot of polynomial curve fit of experimental data at 1.7 lpm. Error bars are the 95 percent confidence limits.

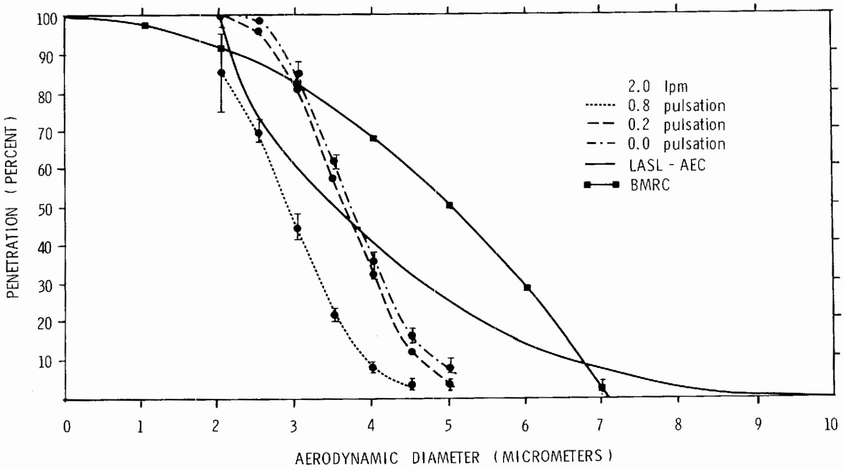


Figure 7 — Plot of polynomial curve fit of experimental data at 2.0 lpm. Error bars are the 95 percent confidence limits.

measured by dividers and rule. The falling speed was calculated from the time-distance relationship of the film image dots. The apparatus was calibrated by placing a microscope stage micrometer in the quiet zone of the apparatus, letting the laser light shine continuously on the micrometer and exposing the film. The micrometer image projected onto the screen served as a calibration scale. Magnification for these measurements was 145x. Typically zero to six tracks were observed for each experiment. Experiments where no tracks were observed were not included in the data. The small number of tracks renders this method applicable only for monodisperse aerosols.

Aerodynamic diameters were calculated using the Stokes relationship

$$V=d_a^2\ g/18\mu \qquad (1)$$

where V is the particle settling velocity
g is the acceleration of the particle due to gravity
μ is the viscosity of air
d_a is the aerodynamic particle diameter, equal to $\sqrt{e}\ d$ where ρ is the particle density and d is the diameter of the sphere.

electron micrographs

During several experiments, particles were collected on electron microscope grids for sizing. The particles were collected on the grid using a point-to-plane electrostatic precipitator identical to the design of Morrow and Mercer.[6] The grids were shadowed with chromium after collection. The electron micrograph magnification was calibrated using a 54864 lines-per-inch carbon replica ruling. The particle diameters were measured on the micrograph and examined for sphericity. Particle density can be calculated from Equation 1 when both the aerodynamic and projected particle diameters are known; the density so obtained was 2.4 gm per cm.[3] Lippman[7] reported 2.56 and Seltzer[5] reported 1.20. The density data does not enter further into the results of this work but was conducted to determine relative uniformity of methods of producing monodisperse aerosol.

measurement of cyclone penetration

Preceding the actual run, the dynamic test chamber was adjusted for the desired velocity; sampling apparatus set up (typically as in Figure 2) and flow rates adjusted; and syringe loaded with colloidal iron oxide sol. The feed to the spinning disc generator was started and adjusted to remove satellites, then the samplers started promptly and as simultaneously as possible. The runs lasted typically from 20 to 40 minutes.

At the conclusion of the run, the cyclones were promptly removed from the chamber. Cyclones were individually placed in separate tubes containing 25 ml 0.05N HCl and placed in an ultrasonic bath for fifteen minutes. While the cyclones were being cleaned, the filters were placed in 5.0 cm diameter plastic Petri dishes. The dishes were counted on the crystal of a gamma ray spectrometer tuned to count solely the 393 Kev energy peak resulting from the photons emitted during the ^{113}In decay. Background counts were determined by counting a blank filter in a Petri dish for 100 seconds. After subtracting the background, the counts were calculated back to a time zero reference (usually the time of the indium elution) using an exponential decay law for the ^{113}In having a half-life (t 1/2) of 103.8 minutes, e.g.

$$S/S_o = (1/2)^n$$

where S is the number of sample counts corrected for background at time t
S_o is the equivalent count at t=0
t is the elapsed time from zero time
t 1/2 is the indium-113 half-life
n is t/tl/2 = number of half lives

After the cyclones were cleaned, a 1 ml aliquot of the cyclone wash solution was placed on a 37 mm filter paper in a 5 cm diameter Petri dish. Thus, both the penetration sample (dry filter) and cyclone retention sample aliquot were counted at the same geometry. Penetration was computed as:

$$\text{Penetration} = \frac{\text{dry filter count}}{\text{dry filter count} + (25 \times \text{aliquot count})}$$

all counts being corrected for background and computed to time zero.

Adequacy of cleaning the cyclone bodies was checked by counting them. Counts on the same order as background (10 to 15 counts per 100 seconds) were obtained. At large cyclone penetration values (90%) the signal to background (S/B) ratio for the cyclone wash was about 2, and the corresponding S/B ratio for the filter was 1000. For penetrations less than 10 percent, S/B was approximately 200 for both.

TABLE I
Equations for Smoothed Penetration Curves

FLOW	PULSATION	RANGE	EQUATION
1.4 lpm	0.0	0 - 2.5	$PEN = 1.001 + 0.01338D - 0.005109D^2 - 0.01388D^3 + 0.004936D^4$
		2.5 - 4.5	$PEN = 4.644 - 5.572D + 3.213D^2 - 0.8671D^3 + 0.01082D^4 - 0.005082D^5$
		4.5 - 9.5	$PEN = 5.002 - 2.107D + 0.3721D^2 - 0.03168D^3 + 0.001054D^4$
		9.5	$PEN = 0$
1.4 lpm	0.3	0 - 2.5	$PEN = 1.001 + 0.01338D - 0.005109D^2 - 0.01388D^3 + 0.004936D^4$
		2.5 - 4.5	$PEN = -0.08780 + 1.029D - 0.2948D^2 + 0.02165D^3$
		4.5 - 9	$PEN = 4.561 - 1.560D + 0.1831D^2 - 0.007975D^3 + 0.00006979D^4$
		9	$PEN = 0$
1.4 lpm	1.3	0 -2.5	$PEN = 0.09968 - 0.01055D + 0.01850D^2 + 0.01355D^3 - 0.01347D^4$
		2.5 - 4.5	$PEN = 2.758 - 2.531D + 1.699D^2 - 0.6676D^3 + 0.1384D^4 - 0.01424D^5 + 0.0005775D^6$
		4.5 - 7.5	$PEN = 2.997 - 1.332D + 0.2211D^2 - 0.01624D^3 + 0.0004453D^4$
		7.5	$PEN = 0$
1.7 lpm	0.0	0 - 2.5	$PEN = 0.9999 - 0.0004971D + 0.0008159D^2 + 0.0006232D^3 - 0.0005970D^4$
1.7 lpm	0.0	2.5 - 4.5	$PEN = 0.6714 + 1.7190D - 0.5332D^2 + 0.04458D^3$
		4.5 - 6.3	$PEN = 9.758 - 4.866D + 0.90190^2 - 0.07364D^3 + 0.002236D^4$
		6.3	$PEN = 0$
1.7 lpm	0.3	0 - 2.5	$PEN = 0.9998 + 0.0002072D + 0.001175D^2 + 0.00001061D^3 - 0.0007530D^4$
		2.5 - 4.5	$PEN = 1.086 + 2.248D - 0.7660D^2 + 0.08530D^3 - 0.002462D^4$
		4.5 - 6.3	$PEN = 10.30 - 5.296D + 1.010D^2 - 0.08461D^3 + 0.002631D^4$
		6.3	$PEN = 0$
1.7 lpm	1.3	0 - 2.5	$PEN = 0.9976 - 0.004462D + 0.01514D^2 + 0.006588D^3 - 0.01115D^4$
		2.5 - 4.5	$PEN = 1.060 + 3.025D - 1.483D^2 + 0.2655D^3 - 0.01623D^4$
		4.5 - 6.3	$PEN = 1.743 - 0.8659D + 0.1597D^2 - 0.01296D^3 + 0.0003908D^4$
		6.3	$PEN = 0$
2.0 lpm	0.0	0 - 2.5	$PEN = 0.9993 - 0.003961D + 0.003328D^2 + 0.004437D^3 - 0.002662D^4$
		2.5 - 4.5	$PEN = 2.587 + 3.593D - 1.122D^2 + 0.1021D^3$
2.0 lpm	0.0	4.5 - 6.8	$PEN = 4.341 - 2.154D + 0.3979D^2 - 0.03244D^3 + 0.0009845D^4$
		6.8	$PEN = 0$
2.0 lpm	0.3	0 - 2.5	$PEN = 0.9992 - 0.003633D + 0.004155D^2 + 0.004267D^3 - 0.003171D^4$
		2.5 - 4.5	$PEN = 2.437 + 3.477D - 1.099D^2 + 0.1005D^3$
		4.5 - 6.3	$PEN = 4.3873 - 2.281D + 0.4402D^2 - 0.03736D^3 + 0.001176D^4$
		6.3	$PEN = 0$
2.0 lpm	1.3	0 - 2.5	$PEN = 1.003 + 0.001513D - 0.01071D^2 - 0.01060D^3 - 0.001956D^4$
		2.5 - 4.5	$PEN = -3.211 + 5.761D - 2.758D^2 + 0.5155D^3 - 0.03368D^4$
		4.5 - 5.8	$PEN = 1.253 - 0.6554D + 0.1269D^2 - 0.01078D^3 + 0.0003393D^4$
		5.8	$PEN = 0$

development of cyclone penetration curves

Curves of cyclone penetration versus aerodynamic particle diameter were generated from the data obtained by the methods previously described. Each pair of points for the cyclones operating under the different flow conditions was used in a general lilnear least-squares curve-fitting Sub-routine, ORTHON2, available from the University of Minnesota, Computer Center Library. The polynomial which produced the best fit in the least-squares sense (by examination of the standard error of estimate and standard error in the coefficients) was used to represent the data shown in Figures 5, 6, and 7. Table I gives the equations representing the curves. For each curve, 45 to 50 pair of data points were available, in excess of the minimum number recommended for the size of the polynomial obtained. The techniques used to generate the aerosol could not reliably produce aerosols smaller than 2μm or larger than 6μm. This was not a serious problem because at 2 μm the penetration is nearly 100 percent and at 6μm is close to zero and would be zero at 7 μm in all cases except one (1.4 lpm and 0.0 pulsation) where zero is reached at 10 μm.

The curves obtained from the initial least squares fit were manually extrapolated to 100 percent penetration at 1 μm and 0.0 percent at 10 μm so that the entire range of interest could be used to determine the cyclone penetration curve E′ (D) for each specific condition. The completed curves were broken into three sections 0<D <3, 2<D<5, and 4<D<10 μm and least squares fits performed on points read from the smoothed curves. In the range of 2 to 6 μm, the smoothed curve data analysis duplicated the original data curve with less than 1 percent deviation. The error bars represent 95 percent confidence bounds calculated from the standard error in the coefficients of the initial least squares best fit of the data.

computation of respirable mass sampled

The cyclone penetration becomes the measured respirable mass when the sampler is used to sample a dust cloud. The ratio of measured respirable mass to respirable mass criteria of both BMRC and LASL-AEC has been calculated for each of the nine penetration curves for assumed log-normal dust dispersions covering the range of 1 to 10 μm mass median and geometric standard deviations from 1.1 to 4.1.

The respirable mass can formally be defined for spherical particles as:

$$RM = \int_0^\infty E(D)\ P(D)\ \frac{(\rho\pi D^3)d}{6}\quad \ln D \qquad (2)$$

where P(D) is the number density function per cubic meter of air for a log-normally distributed aerosols having a geometric mean diameter Dg and geometric standard deviation σg defined by

$$P(D) = \frac{1}{\sqrt{2\pi}\ln\sigma g}\ \exp \frac{-(\ln D - \ln Dg)^2}{2 \ln^2 \sigma g}$$

and $\frac{(\rho\pi D^3)}{6}$ is the mass of a particle of diameter D and density ρ.

E(D) can take several forms, depending upon the definition of the pulmonary deposition curve. According to the respirable mass criterion established for coal mines by BMRC(2) the respirable mass fraction is

$$E(D) = BMRC\ (D) = 1.0\text{-}(D/7.08)^2$$

for 0<D<7.08 and BMRC (D) = 0 for all D <7.08. In the case of the Los Alamos definition of respirable mass fraction(12)

$$E(D) = AEC\ (D)$$

$$AEC\ (D) = 1 \text{ for } 0.0<D<2.0$$

$$\begin{aligned} AEC\ (D) = {} & 6.103034 - 5.987785D + \\ & 2.770594D^2 - 0.6884753D^3 \\ & 0.09342388D^4 - 0.00651553D^5 + \\ & 0.0001825093D^6 \\ & \qquad\qquad\text{for } 2.0<D<8.0 \end{aligned}$$

$$\begin{aligned} AEC(D) = {} & 0.1136477 + 0.03693936D - \\ & 0.01123596D^2 + 0.0007089895^3 - \\ & 0.000006847943D^4 \\ & \qquad\qquad\text{for } 8.0<D<10.0 \end{aligned}$$

$$AEC\ (D) = 0.0 \qquad \text{for all } D>10.0$$

In order to obtain a sample corresponding to one of the two respirable mass criteria, the cyclone should have a penetration characteristic curve identical to one of the two E(D) functions described. The equations representing the smoothed penetration curves were used to compute the ratio of the mass that would be measured as "respirable", called "respirable mass sampled" to the respirable mass as defined by either the BMRC or LASL-AEC criteria. The equation is

$$K = {}_{1}P(D)E'(D)^{3}d\ln D$$
$${}_{1}P(D)BMRC(D)^{3}d\ln D$$

where E′ (D) is the equation describing the cyclone penetration under the conditions of test.

The integrations were carried out to 10 μm, not to infinity, because the integrand falls to zero before 10 μm. Equation 3 was evaluated numerically using the trapezoidal rule. Simpson's Rule was also used and gave results equal to the trapezoidal method. The number of intervals for the numerical quadrature varied between 20 and 1000 per micrometer. Convergence was established after a five-fold increase in the number of intervals gave the same result to four significant figures.

results and discussion

The complete report on this work [14] contains forty tables of K values computed from the data

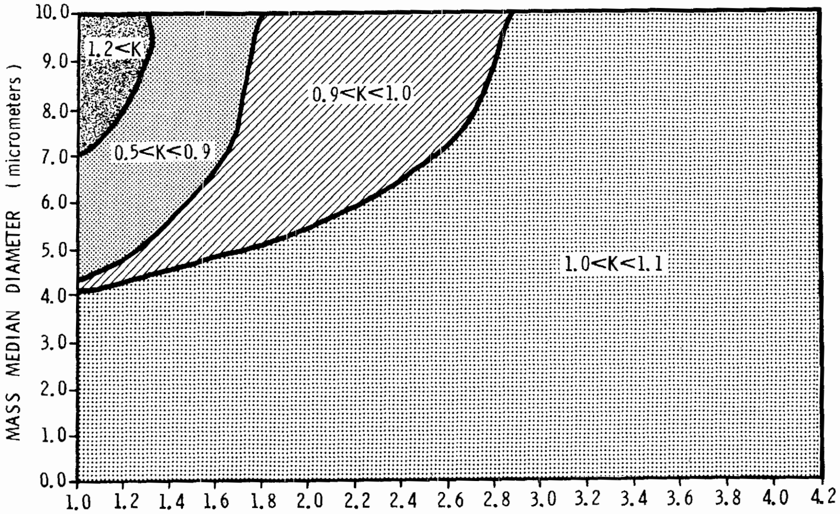


Figure 8 – Values of K, ratio of respirable mass determined by cyclone to that prescribed by BMRC criterion computed for various dust clouds. Flow 1.4 lpm, pulsation 0.3.

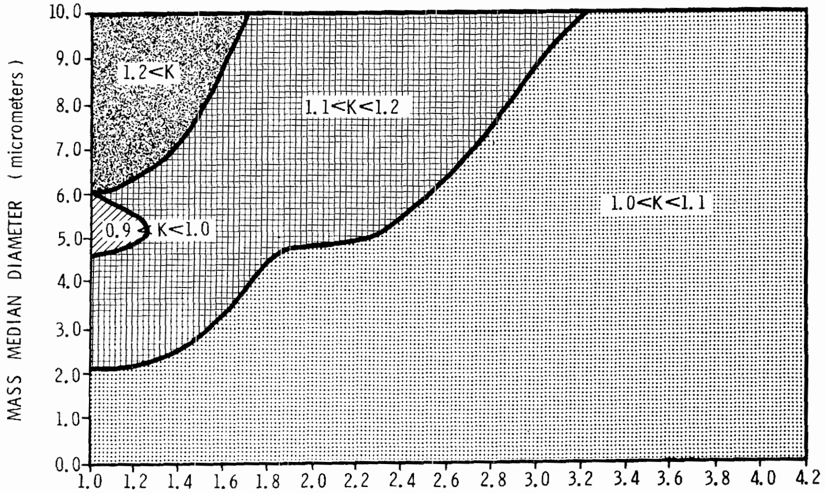


Figure 9 – Values of K, ratio of respirable mass determined by cyclone to that prescribed by BMRC criterion computed for various dust clouds. Flow 1.4 lpm, pulsation 0.0.

using Equation (3), over the following ranges of variables.

Particle diameter---------- 1 to 10μ, both count median and mass median, 1 μm increments

σ_g ------------------------------1.10 to 4.10, 0.2 increments

Flow rate ----------------------------- 1.4, 1.7 and 2.0 lpm

Pulsation ------------------------------------0.0, 0.3 and 1.1

From this tabulation, contour bands of 0.1 intervals of K were prepared. Over the range of variables listed above, K values as low as 0.001 and as high as 1.7 are found. Although the range of aerosol parameters is probably wider than would be encountered in most workplaces, sampling results could be in error from 1000-fold too low to 70% too high if improper choice of flow conditions is used. Contour band charts presented here are limited to those closest to the desired performance.

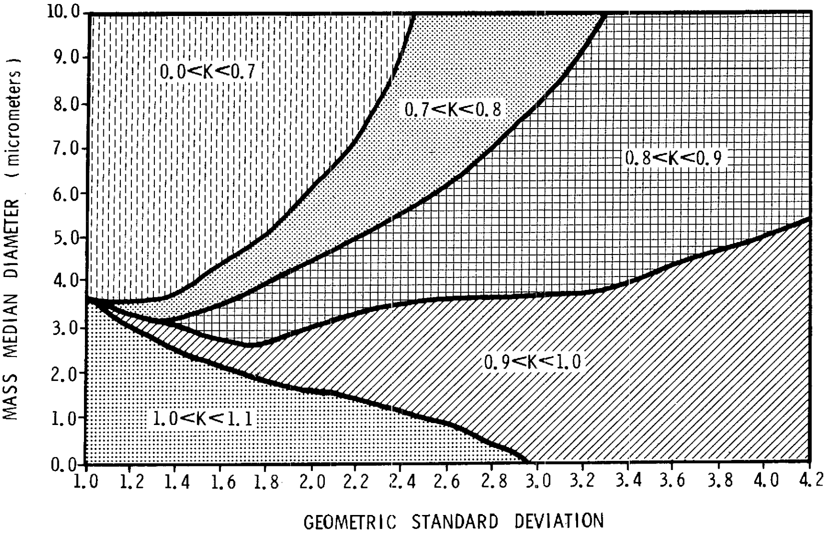


Figure 10 – Values of K, ratio of respirable mass determined by cyclone to that prescribed by BMRC criterion computed for various dust clouds. Flow 2.0 lpm, pulsation 0.0.

comparison to BMRC criteria

Figure 8, representing cyclone operation at 1.4 lpm and 0.3 pulsation, yields 0.9<K<1.1 (± 10 percent error) over approximately 90 percent of the range of interest. In the opinion of the authors, the region of greater error is, in practical terms, of even less significance than portrayed because dust clouds of that characteristic would be unusual and seldom encountered.

Figure 9, 1.4 lpm and zero pulsation, shows a similar pattern, with 1.0<K<1.2, or ±$^{20}_{0}$ percent error compared to the BMRC criterion. If for practical reasons the specification of zero pulsation is important, a correction factor K′ of 1.1 could be assumed in computing equivalency of results, yielding a ±10 percent error in computed equivalent BMRC.

$$K' = \frac{\text{cyclone penetration}}{\text{BMRC criterion}} = 1.1$$

or the equivalent correction factor:

cyclone penetration x 0.91 = BMRC criterion.

Thus a practical resolution would be to sample with the 10 mm cyclone at 1.4 lpm and zero pulsation; correct the respirable mass as measured by a multiplier of 0.91; with results varying from BMRC criteria by ± 10 percent over the entire region of practical interest.

All other operating conditions [14] show markedly greater deviations from a K value of 1, spread over much greater portions of the regions of interest. Other workers [5,8] have recommended 1.4 lpm for the cyclone when compared to the BMRC. Seltzer, *et al.*, in reference 5 does not explicitly call for 1.4 lpm, but his data indicate a smaller error when using a 1.4 lpm.

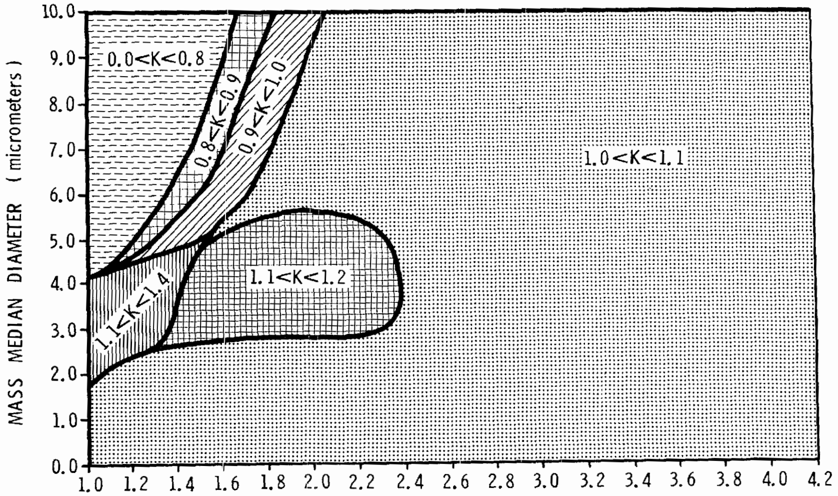
Figure 10 shows 2.0 lpm rate at zero pulsation as specified by the Bureau of Mines. [1] This is not as good a match to the BMRC criterion as either Figure 8 or Figure 9.

comparison to LASL-AEC criteria

For comparison to the LASL criterion, operation at 1.7 lpm and zero pulsation yields results within ± 10% of the criterion over almost all situations to be encountered in practice (Figure 11). Operation at 1.7 lpm and 0.3 pulsation would be marginally better, but has the important practical objection that a controlled degree of pulsation is required.

Other laboratories [5,9,10] have recommended 1.7 lpm for comparison to the LASL criterion. The AIHA [3] recommends 1.7 lpm for comparison to the ACGIH criterion, which is almost identical to the LASL.

Figure 12 shows the conformance to the LASL criterion at 2.0 lpm and zero pulsation, for comparison purposes.

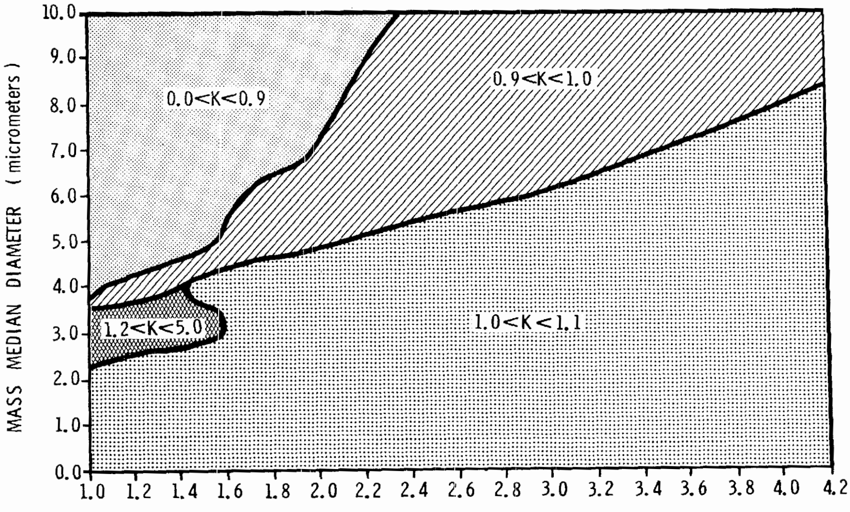


GEOMETRIC STANDARD DEVIATION

Figure 11–Values of K, ratio of respirable mass determined by cyclone to that prescribed by LASL-AEC criterion computed for various dust clouds. Flow 1.7 lpm, pulsation 0.0.

Options to achieve K = 1.0

Obviously, for a respirable mass sampler to yield direct results comparable to a respirable mass criterion, the performance of the sampler must match the criterion. If the penetration of the first stage does not match the criterion, computational correction of the measured respirable mass theoretically *requires* a knowledge of the mass median diameter and geometric standard deviation of the dust cloud being sampled. This requirement largely negates the logistic value of the respirable mass sampler as compared to older methods. If a "practical" solution is sought by depending upon the ranges of diameter and dispersion usually found in occupational exposures and applying a correction factor, the cyclone can be in error by a



GEOMETRIC STANDARD DEVIATION

Figure 12–Values of K, ratio of respirable mass determined by cyclone to that prescribed by LASL-AEC criterion computed for various dust clouds. Flow 2.0 lpm, pulsation 0.0.

factor as high as 2. (See envelopes previously described.) This potential error is uncomfortably high. Furthermore, there will be many situations where the "usual"ranges do not prevail and the error can be very high. The same considerations pertain to conversion of data from BMRC to LASL criteria and vice versa. The conversion *cannot be made*, theoretically, without knowledge of the size and dispersion of the dust cloud.

Two options present themselves:

a. Continued research may develop a sampler whose penetration matches the defined penetration. The 10 mm cyclone, for example at 1.4 lpm and 0.3 pulsation, is fairly close to the BMRC criterion. Continued experimentation would no doubt find a combination of flow rate and pulsation that duplicated the criterion closely. In any such investigation, the frequency of the pulsation would need to be considered as a parameter (it was constant at 38 Hz in this study).

   It is possible that a redesign of the cyclone would also result in matching of the criterion at some reasonable flow rate and zero pulsation. In this regard, the penetration curve represented by the LASL criterion is typical and representative of cyclone performance; the BMRC criterion has a curvature the reverse of that considered typical for cyclones.

b. The physiological data leading to the criteria exhibit a tremendous scatter, as would be expected, which was smoothed by computer modeling of the airway passages of the human being.[11] It is further probable that the physiological data was influenced or biased by the sampling devices then available, viz., the 10 mm cyclone or the BMRE elutriator. While review of the physiological data and resulting committee decisions is not within the scope of the present investigation, it does seem appropriate to at least pose the question: "Can the criterion be modified to match the (now better understood) characteristics of the sampler?". If so, the sampling portion of the environmental investigations would then be on a firm, uniform footing, and a lot of possibly meaningless computational corrections could be eliminated.

No sampling technique will ever be perfect. If the technique reasonably represents the physiological facts, however, the environmental data so gathered will be adequate for enforcement, evaluation, and epidemiological data.

Every effort should be made to reconcile the BMRC criteria and the LASL criteria. The historical reasons for adoption of the BMRC criterion for coal mine dust are understandable. However, the LASL criterion is being (has been, to a degree) adopted for all other pneumoconiosis-producing dusts.

The LASL criterion has all the practical advantages on its side, as compared to the BMRC, because the 10 mm cyclone (LASL) has so many logistic advantages over the BMRC. As a matter of fact, the BMRE instrument which conforms to the BMRC criterion cannot be used, due to its size, weight, and orientation requirements, as a personal sampler. The errors inherent in evaluation of dust exposure by general area sampling instead of personal sampling are far more significant, in the opinion of the authors, than the difference between BMRC and LASL-AEC criteria. Among other things, the shape of the BMRC curve is basically incompatible with the characteristics of ideal cyclone separators.

On the other hand, it seems reasonable to suppose that the physiology of coal miner's lungs is not significantly different than that of other workers in dusty trades. Theoretically, if one criterion is "right", the other must necessarily be "wrong". If, on the other hand, both are "reasonably right", then there would seem to be no *technical* reason why one or the other should not be abandoned.

On the assumption that the LASL criterion is "reasonably right", and in spite of the administrative difficulties involved, a once-and-for-all correction should be applied for conversion of BMRC-based epidemiology to the LASL basis. This could be done, for example, by adjustment of the coal dust TLV and no doubt by several other mechanisms. In spite of the administrative difficulties, such a change would be beneficial in the long run if technically sound.

conclusions and recommendations

1. For application to coal mine dust (BMRC criterion of respirable mass), the best operating mode of the 10 mm cyclone would be 1.4 lpm at 0.3 pulsation, yielding a ± 10 percent error from the BMRC criterion over practically the entire range of interest, without correction factor.

   If for practical reasons zero pulsation is preferred, comparable results yielding $\pm^{20}_{0}$ percent error from BMRC can be achieved by sampling at 1.4 lpm, zero pulsation, and multiplying the measured respirable mass by a factor of 0.91.

   All other operating modes tested failed to yield results that would permit the application of a single correction factor over the ranges of size and dispersion of interest.

2. For application to other pneumoconiosis-producing dust (LASL-AEC and ACGIH criteria) the best operating mode of the 10 mm cyclone is 1.7 lpm, zero pulsation. This will yield measured respirable mass within ± 10 percent of the criteria, without correction factor, for almost all situations to be encountered in practice.

3. It is inescapable that for a sampler to measure the respirable mass as defined, its first-stage penetration must match the defined characteristic. If it does not, computational correction of results requires an independent knowledge of the particle size and dispersion of the cloud being sampled. This requirement largely negates the logistic value of the personal sampler.

4. Conversion of data from BMRC to LASL-AEC criteria, and vice versa, is subject to the same consideration as item 3 above.

5. Two options present themselves:

   a. Further experimentation with flow rate and pulsation could lead to a closer match to the criteria. Cyclone redesign could lead to a better match of the LASL criteria. The shape of the BMRC curve is incompatible with cyclone penetration curves in general (see discussion).

   b. The physiological data should be reviewed to determine whether it would be technically acceptable to modify the criteria to match the (now better understood) characteristics of the sampler (see discussion).

6. The BMRC and LASL criteria should be reconciled, and one abandoned, so as to achieve a uniform criteria. There would seem to be no physiological basis for two criteria. The epidemiological basis could probably be modified and reconciled. The LASL criterion would appear to have more practical advantages than BMRC (see discussion).

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Accepted August 2, 1976